Fuel Cell Research at NASA GRC

By
Marla E. Pérez-Davis

An overview of NASA GRC initiatives and challenges in fuel cell technology. The research and development of fuel cells and regenerative fuel cell systems for a wide variety of applications, including earth-based and planetary aircraft, spacecraft, planetary surface power, and terrestrial use are discussed

Fuel Cell at NASA GRC

Prepared for OakRidge National Laboratories (ORNL)

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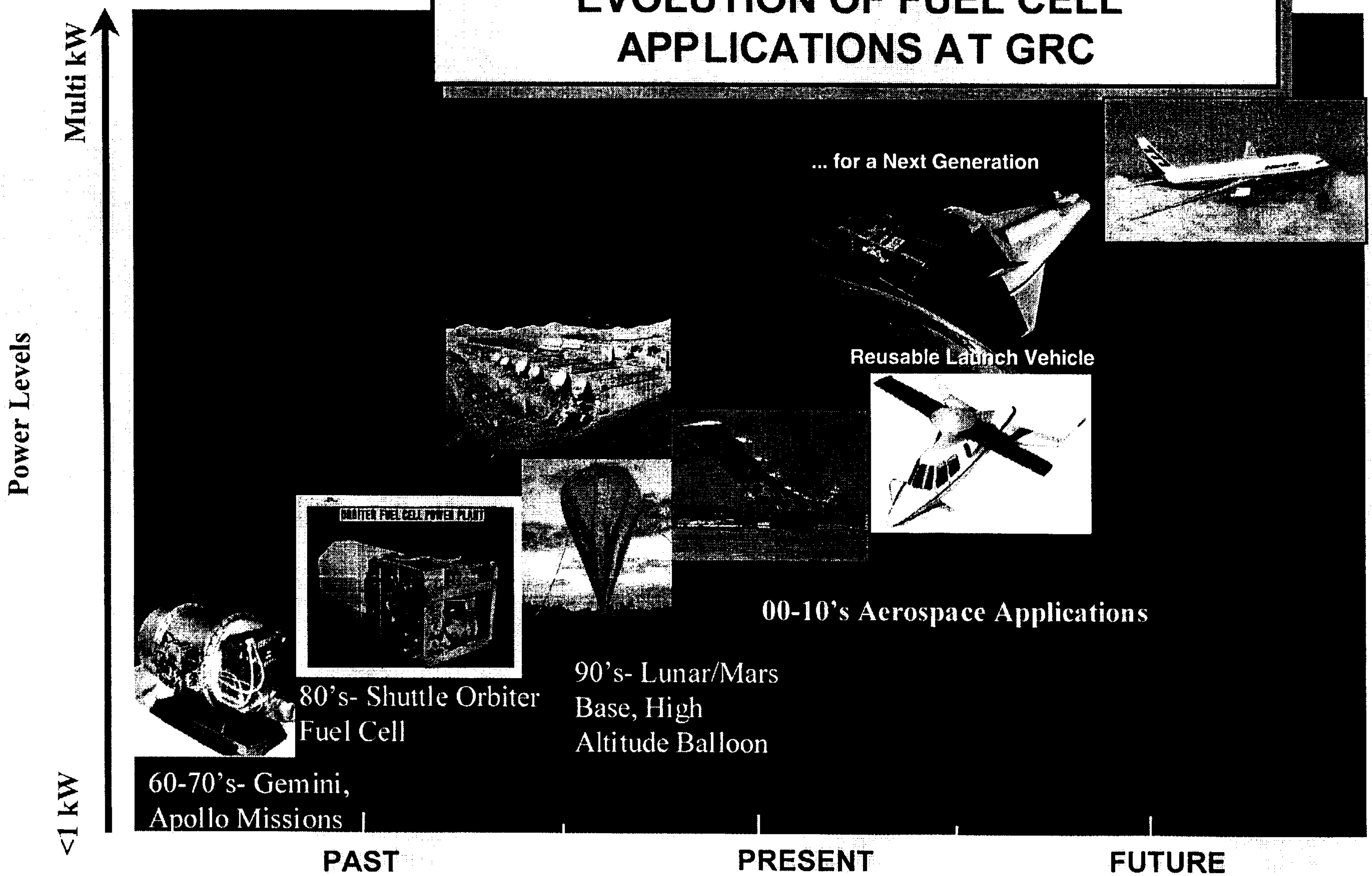
EVOLUTION OF FUEL CELL APPLICATIONS AT GRC



Glenn Research Center

Electrochemistry Branch

at Lewis Field

NASA has a long history in Electrochemistry Power Technology

The NASA Glenn Research Center (GRC) has decades of experience in the development of fuel cell technologies for NASA missions and programs.

The 1970's

- GRC was responsible for advancing the state of fuel cell technology to a level that qualified it for the shuttle onboard power system. Parallel technology advancement programs on the Gemini proton exchange membrane (PEM) fuel cell and the Apollo alkaline fuel cell were conducted at GRC.

The 1990's

- GRC led the team to produce the DOE's 10-year Fuel Cells for Transportation Plan. GRC also continued to address the RFC PEM energy storage concepts for Space Station, high-altitude balloons, and high altitude aircraft.

The 1980's

- GRC continued to work to improve the life and performance of alkaline fuel cell technology chosen for use on the Space Shuttle.
- GRC conducted a study of the feasibility of using a PEM fuel cell in an electric vehicle that served as the impetus for the PEM fuel cell program for electric vehicles.
- GRC culminated management of the DOE/Gas Research Institute Phosphoric Acid-Fuel Cell program with a 40-kW powerplant field test, as well as stack and balance-of-point plant technology development for 200-kW, 7-5-MW, and 11-MW powerplants.
- During this period, GRC also examined regenerative fuel cell (RFC) energy storage concepts for Lunar/Mars applications in support of the Space Exploration Initiative.

WHAT NASA IS DOING NOW

Regenerative Fuel Cells

- Develop passive ancillary component technology to be team with a hydrogen-oxygen unitized regenerative fuel cell (URFC) stack to form a revolutionary new regenerative fuel cell energy storage system for aerospace applications
- Minimize parasitic power losses allowing the RFC to operate as an H_2/O_2 battery by replacing active RFC ancillary components with passive components.
- Demonstrate an integrated passive 1-kW URFC System.

High-Altitude Aircraft such as the ERAST Helios Prototype

Fuel Cell Stack Technology for Reusable Launch Vehicles (RLV's)

- Proton Exchange Membrane fuel cell (PEMFC) technology offers the following major advantages over existing alkaline fuel cell (AFC) technology for space vehicle applications
  - Enhanced safety
  - Longer life
  - Lower weight
  - Improved reliability and maintainability
  - Higher peak-to-nominal power capability
  - Compatibility with propulsion-grade reactants
  - Potential for significantly lower costs

Fuel Cell Power Plant Development for

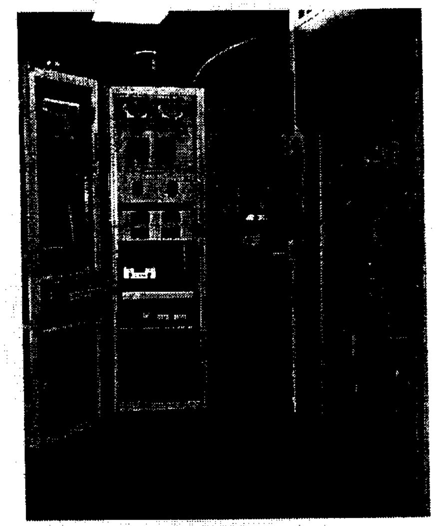
- Breadboard and engineering model PEMFC powerplant development and prototype program.
- Modular approach allows NASA to leverage the evolving and highly competitive commercial market in PEMFC technology, assuring technology transfer and low costs well into the future.

Fuel Cells for Low-Emission Commercial Aircraft

- Focused on the elimination of CO_2 emissions from civil transport aircraft by conversion of their propulsion systems to hydrogen fuel, and by the introduction of new energy conversions technologies.
- Next-generation fuel cell will develop and demonstrate revolutionary energy conversion technologies to achieve reduced emissions aircraft operations. Areas under consideration include cell chemistries and advanced materials, and novel cell, stack, component, and system design. The power range being analyzed is from 100 kW to 90MW

Regenerative Fuel Cell Energy Storage for Renewable Energy Systems

NASA GRC Fuel Cell Facilities



Fuel Cell Facilities

- Fundamental Component Development and Evaluation
- Individual Fuel Cell, Electrolyzer and Ancillary Testing
- Three Test Cells for Stack and System Testing

Electrochemical and Structural Characterization Facilities

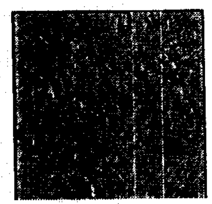
- Fundamental investigations to develop breakthrough electrochemical technology for the next generation of batteries and fuel cells

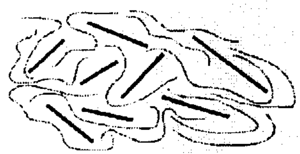
NASA GRC Fuel Cell Facilities

Facility	Capabilities
Fuel Cell, Electrolyzer, and Ancillary Test Facility	Performance, load following control, and life testing of individual fuel cell and electrolyzer stacks and ancillaries
Regenerative Fuel Cell System Evaluation Facility	Performance and life testing of closed loop regenerative fuel cell systems
Primary Fuel Cell System Evaluation Facility	Performance and life testing of primary fuel cell systems
Electrochemical and Structural Characterization Facility	Structural, electrical, thermal, and electrochemical characterization of advanced materials for batteries and fuel cells
Fuel Cell Component Development and Evaluation Facility	Development and evaluation of advanced fuel cell chemistries, materials, cell configurations, fuel storage technologies, and ancillary components

Multidisciplinary Approach

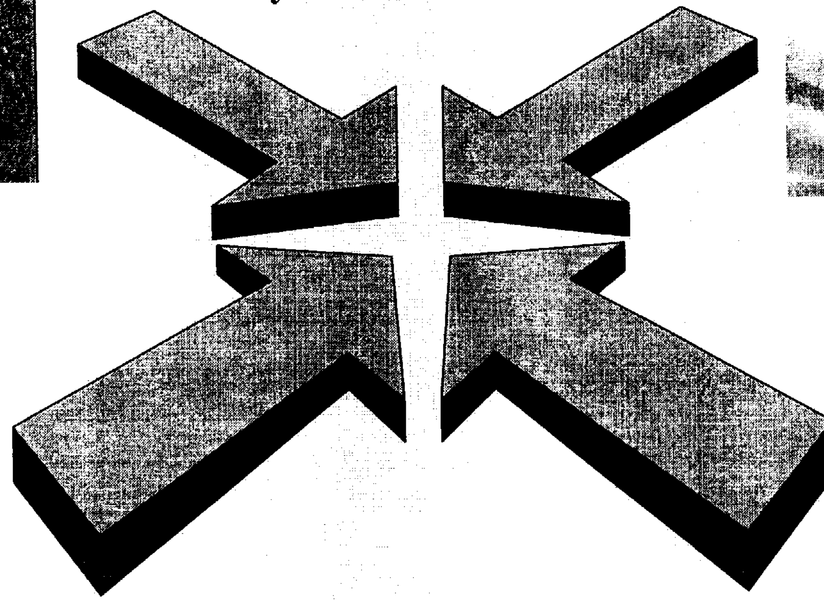
Materials Research





Thermal Management

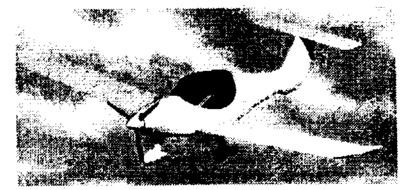
System Controls

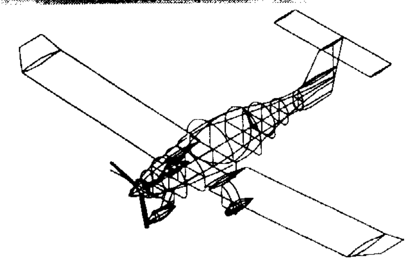


Fuel Cell component design and testing

PMAD

System Analysis

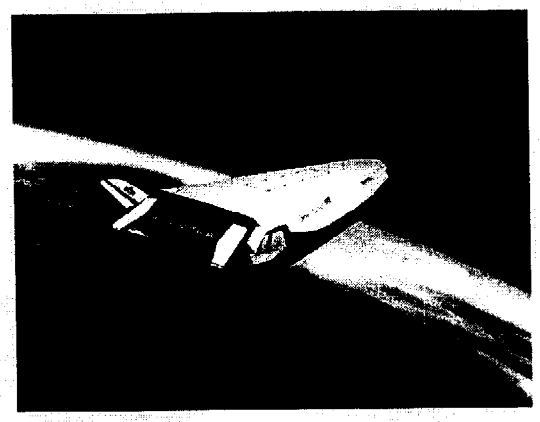




Facilities for Testing in Relevant Space and Aeronautics Environments

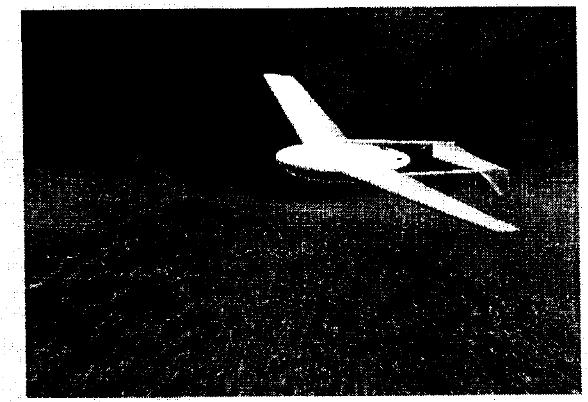
NASA GRC has the expertise and capabilities essential to the successful development of advanced fuel cell power systems for space and aeronautics applications

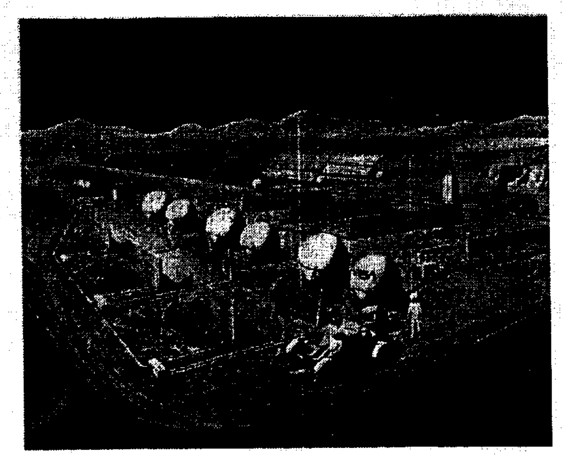
Space Applications for Fuel Cell Power Systems



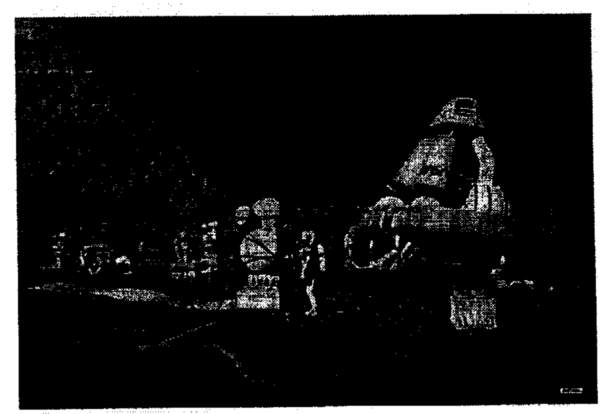
Reusable
Launch
Vehicles

Planetary
Aircraft



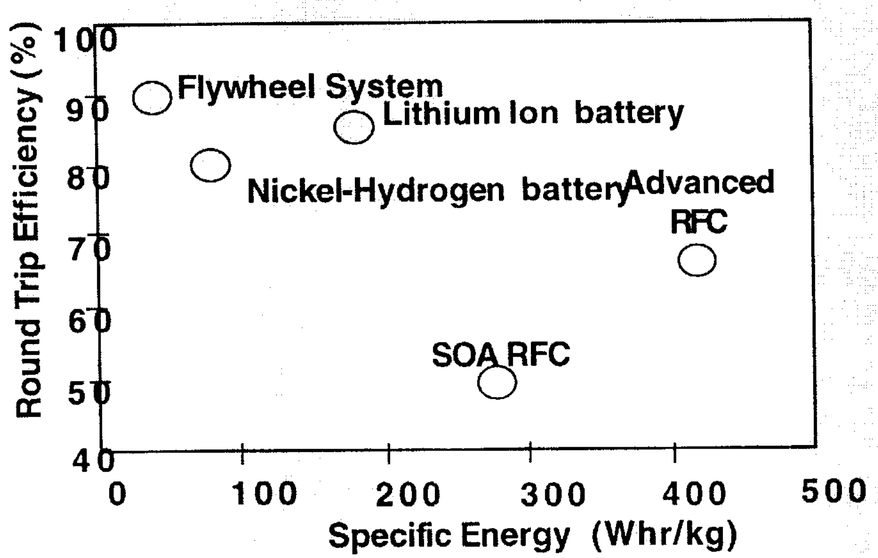


Planetary
Surface
Power



Regenerative Fuel Cell (RFC) for Energy Storage

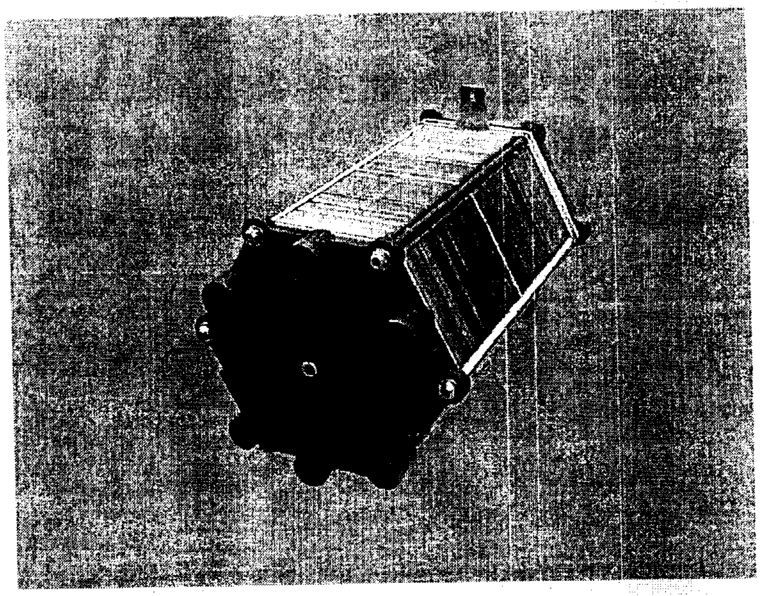
Demonstrate feasibility of passive ancillary component technology (fluids, mechanical,thermal) to form revolutionary RFC energy storage system for aerospace applications with >400 Wh/kg energy density



Comparison of Energy Storage Devices (12 hr/12 hr cycle)

2nd Generation Space Transportation

Proton Exchange Membrane Fuel Cell (PEMFC)

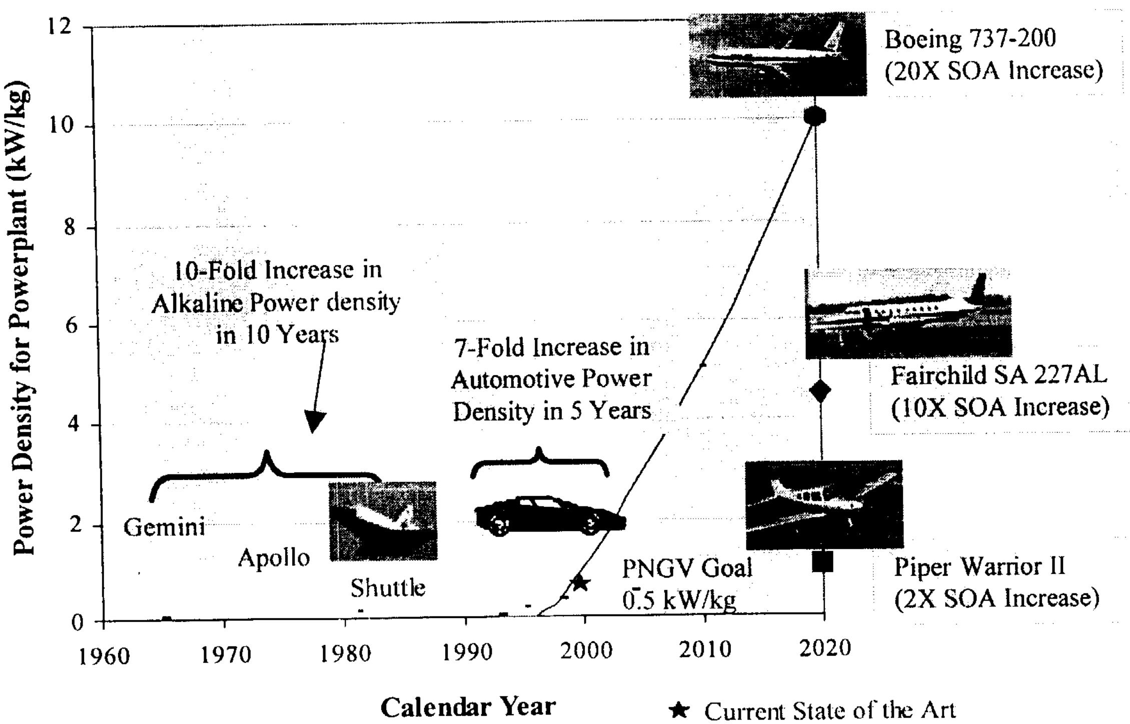


- Products: Competitive Development & Testing of PEMFC Systems
- Benefits
  - Safety:
    - Reduced Hazardous Materials in Fuel Cell Stack
    - Reduced Critical Failure Modes
  - Durability/Supportability:
    - PEMFC Stacks Eliminate Corrosion/Limited Life Inherent to Alkaline
    - PEM Accessory Section to Incorporate More IVHM to Reduce Ground Servicing
  - Cost:
    - Evolving and Highly Competitive Commercial Market
    - Reduced Life Cycle Costs in Logistics w/Potentially Longer Life Powerplants

Implementation / Metrics

- Current State of the Art
  - PEMFCs actively being developed for commercial applications (automotive, residential markets)
- Performance Metrics
  - 2-20 kW steady state performance
  - </= 13 lbs/kW
  - 10,000 hr. life
- Risks: Only NASA is Developing PEMFCs for Space Environment
  - System Water Management under Flight Conditions
  - Materials Compatibility with Pure O2 Reactant
- USG Participants: GRC (Lead), JSC, KSC, MSFC

Technology Innovation: Revolutionize Aviation



Technology Challenges

- ✈Light weight and/or micro-components using nanotechnology materials
- ✈Innovative Fuel Cell Stack (Anode/Electrolyte/Cathode optimization) and Components for High Power Density
- ✈Reformer technologies
- ✈Highly efficient motors (e.g. supercondutivity motor)
- ✈Integrated Miniaturized Power Distribution Systems
- ✈Ultra High Energy Density Power Sources and Hybrid System viability

"Breakthrough" propulsion technologies needed to enable a safe, environmentally friendly expansion of aviation

Air Breathing Fuel Cell Technology

Analytical

Conceptualize and Evaluate Innovative Fuel Cell and Hybrid Systems for Aircraft Propulsion and Airport Operations

Air Breathing Fuel Cell Stack Model

Analysis and Improvement of Fuel Cell Power / Propulsion System Design

- Establish Limits and Capabilities of Fuel Cell Powered Aircraft
- Various Aircraft Classes
- Various Configurations (Hybrids)

Air Breathing Fuel Cell Power / Propulsion System Model

PowerPlant Active System Control Algorithms (Optimize System Performance)

Air Breathing Fuel Cell Technology

Experimental

Characterize SOA Proton Exchange Membrane and Solid Oxide Fuel Cell Stack Performance

Design, Fabricate and Test 1 - 5 kW Breadboard Fuel Cell System

Analytical

Conceptualize and Evaluate Innovative Fuel Cell and Hybrid Systems for Aircraft Propulsion and Airport Operations

Identify Advanced Technology Metrics / Goals (kW/kg, kW/l, Turn-Down Ratio.) for Fuel Cell Propulsion System and Components

XGen Fuel Cells

Objective:

Develop and demonstrate revolutionary energy conversion technologies to achieve reduced emissions aircraft operations

Potential Benefits:

- Develop enabling technologies for fuel cell based aircraft power and propulsion systems
- Continued power density improvements will be achieved by: *improved system and component design, advanced lightweight materials, performance improvements, innovative concepts/designs, improved fuel storage.*

  Goal: 10 kW/kg by 2020
- Substantially reduce contribution of emissions from the aviation sector to climate change and degradation of local air quality and the ozone layer.

XGen Fuel Cells

Technical Approach:

Multidisciplinary approach that includes:

- investigation of fuel cell chemistries
- advanced materials development
- novel cell, stack, component, and system designs

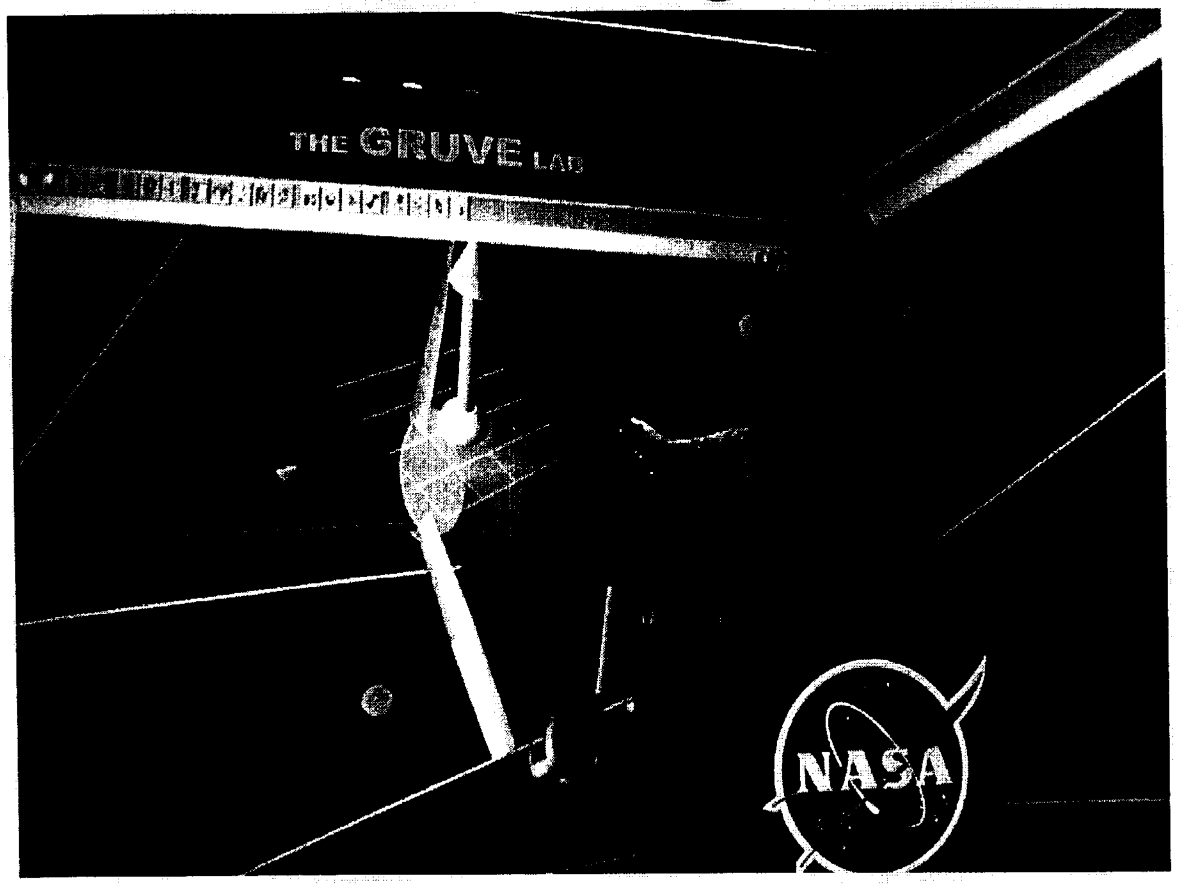
Subtask 1: Fuel Cell System Concept Generation and Analysis

- Generate conceptual designs of fuel cell and hybrid systems for both near term and advanced technology concept
- Evaluate concepts based on mass and volume density, cost, safety, manufacturability, reliability, and impact to existing infrastructure

Subtask 2: Investigation of Advanced PEM Materials

- Develop new proton exchange materials that have good stability and performance at temperatures up to 200°C.
- Investigate the use of lightweight fiber reinforced composite materials in fuel cell environments

Fuel Cell Integrated Environment



- Visualization technique
- Fuel cell modeling
- Analysis of layout

Virtual reality provides engineers and scientists the opportunity to interact with complex design concepts in unique ways

NASA Propulsion systems analysis

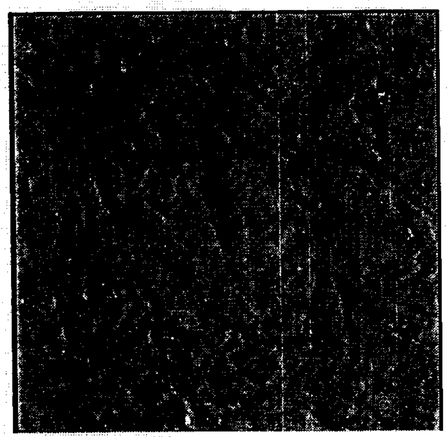
- GRC: Leads NASA aeropropulsion systems analysis
- LaRC: Leads NASA airframe systems analysis
- Typical tasks include:
  - Design optimization and sensitivity studies of new technologies applied to an engine
    - e.g. better materials allow a higher turbine inlet temperature, which produces a higher thrust
  - Determination of potential of new system designs
    - e.g. evaluation of combined rocket/turbine cycles for access to space
- Modeling capabilities include:
  - Thermodynamic cycle analysis
    - NPSS (Numerical Propulsion Systems Analysis) - 1D thermo code
  - Weight/Volume prediction
    - WATE flowpath code
  - Cost prediction

Current efforts

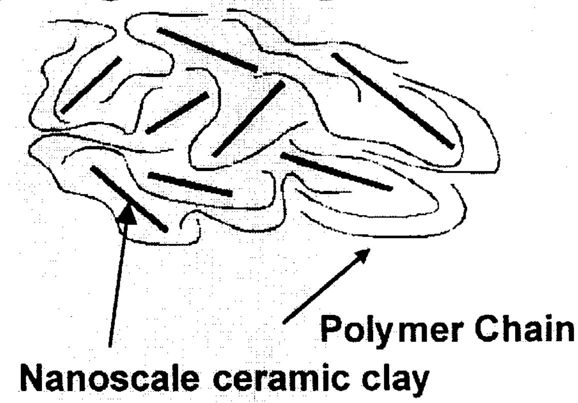
- Incorporation of fuel cell elements into NPSS code
  - Uses existing NPSS capabilities
    - thermodynamic data
    - optimization algorithms
    - gas turbine models for hybrid systems
    - off-design modeling
      - altitude, part-power
    - transient modeling
- Investigating system configurations
  - PEMFC, SOFC
  - Turbines, heat exchangers, electric motors
- Investigating system applications
  - GA power/propulsion
  - Business jet hybrid power/propulsion
  - APU power
  - High altitude airship regenerative power/propulsion (with photovoltaics)

Materials Research Areas

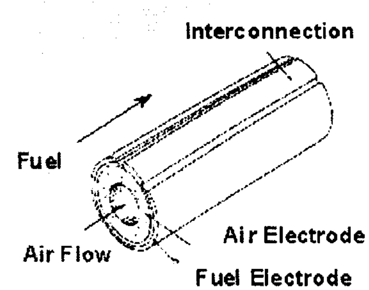
- Development of New Polymeric Proton Exchange Membranes



- Light Weight Composite Hydrogen Storage Tanks



- Improve strength and fracture toughness of YSZ electrolyte for SOFC applications



Objective

- To Develop New Proton Conducting Membranes that Can Operate Effectively in a Fuel Cell Above 120 °C
- Low Cost

Ceramic Solid Oxide Fuel Cell Development Effort in ZCET Project

Goals/Objective:

- Improve strength and fracture toughness of yttria stabilized zirconia (YSZ) ceramic solid oxide fuel cell electrolyte

Approach:

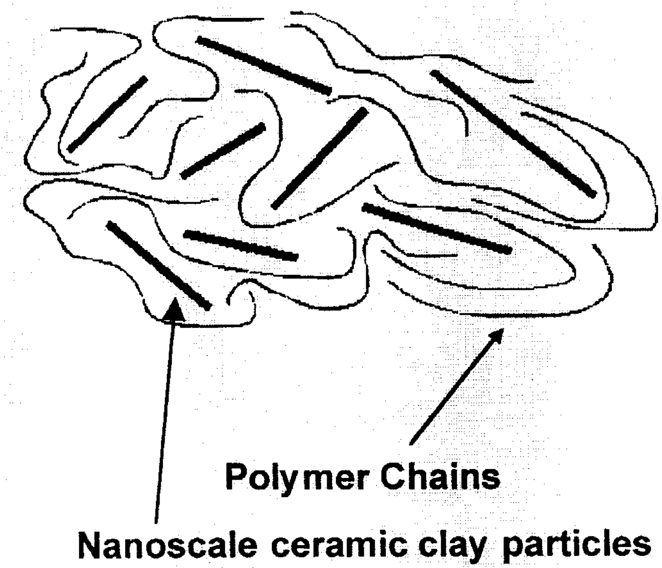
- Reinforce YSZ with alumina to produce a composite solid electrolyte
  - increase in strength and fracture toughness expected from composite theory

Technical Challenges:

- Fabrication of dense YSZ-alumina composites
- Increase in strength and fracture toughness without sacrificing ionic conductivity of electrolyte

Zero CO2 Emissions Technologies
LH2 Tank Material & Insulation

- ***Material Innovation:***
  - *Liquid Hydrogen fuel tanks must be lightweight, strong, and stiff without allowing hydrogen to escape.*
  - *Liquid Hydrogen fuel tanks must perform at both cryogenic and environmental temperatures.*
  - *Nanocomposite materials have the potential to reduce hydrogen permeability in lightweight Polymer Matrix Composite (PMC) fuel tanks.*
  - *Carbon fiber reinforced composite materials have a very high specific strength (Strength to weight ratio).*
- ***Insulation:***
  - *Insulation must protect the cryogenic liquid inside of the tank as well as provide thermal protection for the tank itself.*
  - *Insulation needs to be lightweight and efficient while still providing good mechanical connection to the tank throughout the tank's temperature range.*

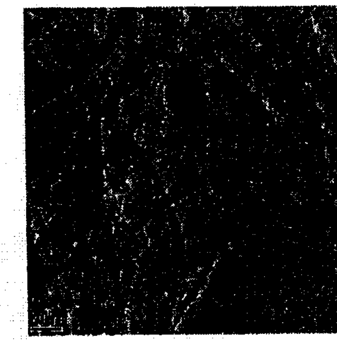


Goals:
- *10 - 20% toughness improvement*
- *15 - 40% strength improvement*
- *30 - 60% permeability reduction*

What Do We Want in a Tank Material?

- Light weight.
- Strong – must resist flight loads & internal pressure.
- Tough – must resist micro and macro cracking at cryogenic temperatures, cycle.
- Useful T_g – must not degrade at moderately high temperatures (~150 °F).
- Compatible with insulation.

PMC Structural Components for Fuel Cells



Objective: Reduce fuel cell weight through the use of lightweight materials in structural components

Approach: Investigate the use of polymer matrix composites in fuel cell bipolar plates

- Optimize composite electrical and mechanical properties
  - Conductive reinforcements – conductive fibers, nanotubes, conductive polymers
  - High modulus fibers and/or nanotubes for enhanced strength and stiffness
- Utilize low cost manufacturing methods
- Assess long-term durability in simulated fuel cell environment
- Validate performance and durability in fuel cell

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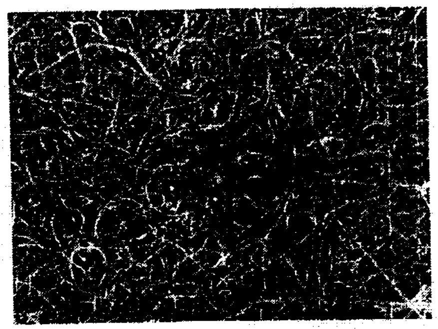
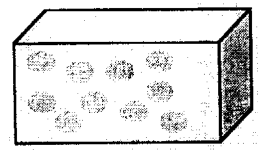
Electrochemistry Branch

at Lewis Field

Chemical Functionalization is the Key to Nanotube Applications

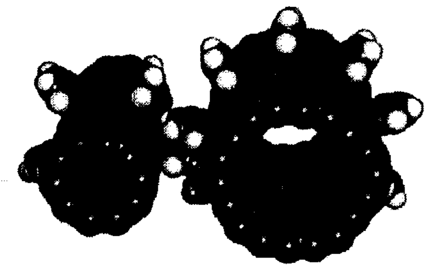


Nanotube Felt
(as received)
- Difficult to separate
- Insoluble
- Aggregate in certain media

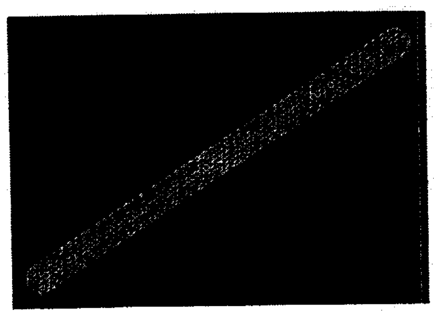


Nanotube Composites

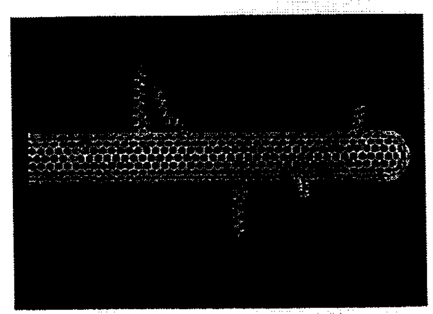
Nanotube Arrays



Nanotube Gears



Unfunctionalized Nanotubes

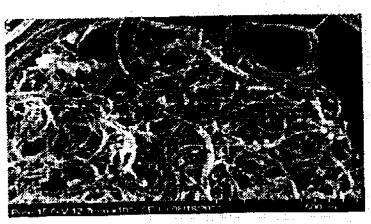


Side- Wall Functionalized

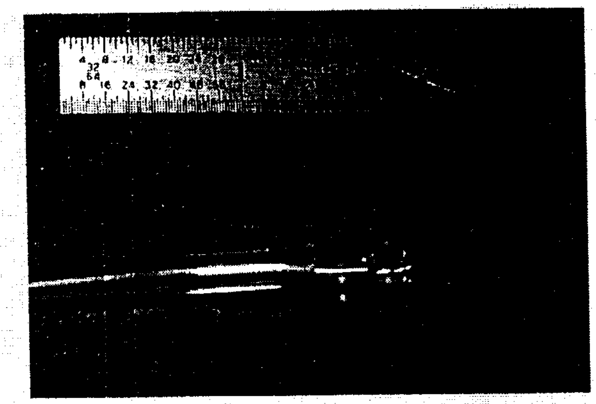
End-Wall Functionalized

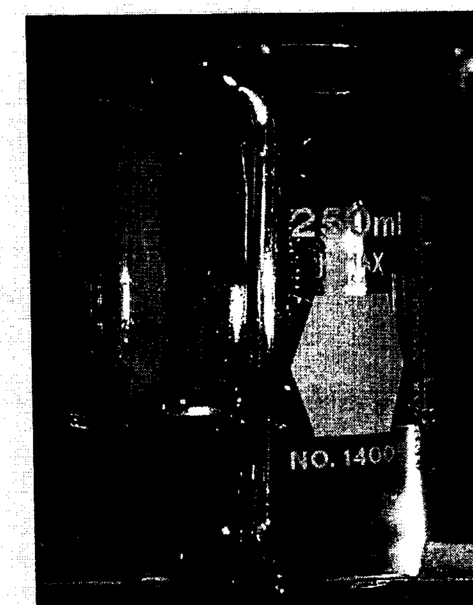
NanoEnergy Storage

Assessment of the "practical" technical feasibility of utilizing nanotubes for revolutionary energy storage concepts: (a) hydrogen storage, (2) hydrogen/air battery



Carbon Nanotubes





Electrochemical cell for preliminary electrochemical and impedance measurements.

The use of nanotechnologies for energy storage may allow for lighter and more efficient batteries and fuel cell cell systems. Lighter weight, lower volume energy storage systems will have significant impact on NASA's missions.

NASA GRC Expertise and Capabilities

NASA GRC has the expertise and capabilities essential to the successful development of advanced fuel cell power systems for space and aeronautics applications

- System analysis
  - Fuel cell subsystem modeling
  - Aircraft performance modeling
  - CFD analysis
- Fuel cell component design and testing
  - Cell and stack-level
  - Reactant storage
  - Ancillaries
- Fuel cell subsystem design and testing
- Power management and distribution
- System controls
- Fuel cell materials research
- Thermal management
- Advanced motor development for electric propulsion
- Full scale power system testing
- Facilities for testing in relevant space and aeronautics environments

Partnerships/Collaborations

Federal Agencies

SBIR"s

Academia

Private Industry